Risk Panel Report

Executive Summary

In early January 2009, at the request of the Director of Accelerators at CERN a panel of experts was assembled to assess the risks associated with turning the LHC back on after the proposed repairs to the various accelerator systems following the incident of September 19, 2008 are completed. The panel members with the exception of one member are not involved in the day to day activities of the repairs. The panel members expertise covered the spectrum of accelerator systems associated with the LHC and all have had first hand experience with similar systems. The members of the Risk Panel are listed in Appendix 2. Appendix 1 is the charge to the Panel from the Director of Accelerators, Dr. Steve Myers.

Several members of the Panel were able to attend the LHC Performance Workshop (Ref. 1) held in Chamonix during the first week of February this year. This was the first meeting of these panel members and the venue provided an opportunity to listen to the detailed planning and progress of the repairs to the LHC along with the dramatic accomplishments in commissioning the world's most complex accelerator before the incident. The agenda of the Chamonix workshop is available at http://indico.cern.ch/conferenceDisplay.py?confId=45433 and the transparencies for the presentations are accessible from this location. The atmosphere in Chamonix provided the opportunity for one on one conversations with the people carrying out the repairs by panel members which was very productive.

On March 5 and 6, the full panel met with members of CERN staff to complete our information gathering to assess the risks. The agenda for this final meeting is given in Appendix 3. Again as in Chamonix the presentations and discussions that followed were detailed. Several of the topics were follow-ups on the discussions in Chamonix and others were new. These included the reliability of the kicker systems, the reliability of the control system environment, the site power, and further exploration of the machine protection systems.

The Panel would like to thank the CERN team for the opportunity to attend the Chamonix LHC Performance Workshop and the opportunity to discuss the progress on repairing the LHC at CERN on March 5th and 6th. The frank discussions with the people carrying out the work have been invaluable in helping us reach our conclusions and in developing our recommendations. In addition, access to the preliminary report of the Internal CERN Task Force led by Phillipe Lebrun was also very helpful in our considerations. Their final report is now available (Ref. 2). We concur with their conclusions and recommendations.

Anything that could lead to an incident that would interrupt the operation of the LHC for a period of more than half a year is considered by the Panel to be an unacceptable risk. Faults that lead to one to two month interruptions, like a thermal cycle for the cooling tower maintenance or an isolated component failure, should be avoided but realistically are part of the operation of an accelerator system as complex as the LHC. With this in mind we have come to the following observations and recommendations. Following these observations and recommendations are the more detailed comments and observations that amplify the observations and recommendations given here in the summary.

1. At the close of the Chamonix Workshop, there was a general feeling among the Panel members that the initiating fault for the incident in Sector 34 was a high resistance in the splice area of the dipole bus between the dipole magnet and the short straight section containing Q24. During the March visit to CERN the presentation on the 13 kA splices listed a number of attempts to reproduce a splice with a 200 nΩ resistance using standard components that all gave resistances of 10 nΩ or less. While a high resistance splice is still the most likely origin, other possible causes cannot be excluded.

2. The Panel supports the recommendation of the QPS Panel concerning not powering the LHC to high currents until the fully upgraded Quench Protection System is in place and is fully commissioned and validated. Low current operation may be desirable for further investigation of possible high resistance joints in the magnet systems.

3. The situation with the Quench Protection System for the 6 kA bus is in flux. The current configuration includes the magnets along with the bus in the voltage sensing circuit. The Panel is concerned that a complete analysis including the energy deposition in the superconductor (miits) was not available. This analysis should be done immediately and based on the findings, the QPS system should be modified as needed. The 6 kA circuits should not be operated at high currents until this is completed.

4. The inner triplet system is in a similar state. The Panel recommends that a similar analysis be carried out for this key system.

5. The quench protection for the 600 A buses, of which there are many, should be clarified and system modifications should be made if needed to provide adequate protection.

6. The Panel notes that the co-mingling of the 600 A buses with the Main 12 kA Quadrupole bus may present a failure mechanism where an arc due to failure of an ultrasonic weld of the 600 A bus under power could cause significant damage to the 12 kA bus. If at the same time, the fast current dump system for the Quad circuit were to be energized, the voltage across the Quad bus could initiate a high energy arc across the Quad bus leading to an incident similar to Sept. 19.

7. The Panel is pleased with the improved quality assurance procedures (accurate temperature measurements, photographic records, ultrasonic scanning, etc) that have been set up for the interconnections of the new magnets that are being installed in the damage region of sector 34. The Panel believes that this will significantly reduce risk for the new splices made following the new procedures.

8. The Panel feels that the re-installation of the magnets in sector 34 presents an opportunity that should not be missed to apply an enhanced clamping system for these high current splices to further insure long term reliability of these key elements of the magnet circuit.

9. The Panel recommends that a bottoms-up analysis be carried out to prioritize the investment in the spares inventory and/or machine safety systems to minimize the risk of an extended shutdown (> 6 months) due to an incident. This is motivated by the limited spares inventory of key magnet elements like the final focus triplets and the large number of unique magnets and feed boxes. Some of these elements would have a lead time of several years to replace which places a premium on making sure that they are adequately protected by the machine protection system. A comprehensive policy with respect to spares and component safety needs to be developed.

10. The RF cavities on the sector 34 side of IP4 shut down on He overpressure during the incident of Sept. 19. The interior condition of these cavities is not known although there is every indication from the beam line pressure gauges that there was no increase in the internal cavity pressure. To verify their operational readiness, every effort should be made to operate these cavities at the earliest possible date. If there is a problem, there would then be sufficient time to carry out the needed repairs in parallel with the rest of the work on sector 34.

11. The RF cavities have a very long lead time for replacement and the Panel is concerned about migration of MLI during LHC operation. Some effort should be invested in studying the development of a trapping system for MLI particles to prevent their entering the cavities. A small particle of MLI entering an operating cavity will destroy the superconducting surface of one of the cavity cells requiring removal of the cryomodule.

12. A sudden increase of the beam tube pressure to atmospheric pressure adjacent to the cavities would result in an overpressure of the He vessel to ~ 12 Bar due to the rapid vaporization of the liquid He. This would crush the cavities and their replacement would take at least one year without adequate spares. This nearly happened during the Sept. 19 incident due to the distortion of the tunnel isolation doors that capture the beam pipes. The Panel recommends that these beam pipes be protected to prevent such an event.

13. The Panel endorses the RF group's approach for cavity spares and urges them to proceed with procuring four new cavity modules so that there would be sufficient spares to complete an additional RF cryomodule (four cavity modules) using the cryomodule removed from service. There is one complete cryomodule that is about to be tested. This would provide one complete tested spare and the components needed to refurbish an existing cryomodule quickly to provide an additional complete cryomodule. The procurement of any new cryomodules should include the redesign of the helium venting system with sufficient cross section to avoid overpressuring the cavity module to the point of failure.

14. The LHC Control System provides machine control for at least 10 minutes in the event of a complete loss of power to the control room. This allows in principle an orderly shutdown of the LHC to a known safe state. The addition of a Diesel powered generator for the power supply could maintain the control room operation until power was restored. The server room next door to the Central Control Center has the water cooling piping for the servers installed in the ceiling above the servers. A failure in this piping could effectively destroy a significant fraction of the servers which have a six month lead time for replacement. This risk should be mitigated by installing appropriate shields to control the water flow from such a failure.

15. The current schedule adopted just after the Chamonix Workshop is a very aggressive one with little or no contingency. Since its adoption, there have been several other significant work packages added including adequate quench protection for the 6 kA bus. It is paramount to maintain quality and safety while aggressively working to stay on schedule to insure long term reliability of the LHC. The Panel recommends strongly that quality work take precedence over maintaining schedule to minimize risk for the long term operation of the LHC.

16. The Panel continues to be concerned that not all the DN200 cryostat pressure relief valves will be installed when the LHC starts up later this year. While using the instrumentation ports on the short straight sections as pressure relief valves would provide adequate protection for an event similar the incident on September 19, it would not for the maximum credible incident. If for some reason there is additional schedule delay, management should seriously consider outfitting the rest of the LHC with the DN200 valves before startup of the LHC.

17. Independent of the above, the Panel recommends that a satisfactory solution be developed to mitigate the risk associated with the thought that it is currently thought not possible to install the DN200 valves on the two Q6s and the eight DFBA's in the cold sectors of the LHC before starting up the LHC.

18. The Panel is continuing to investigate the vulnerability due to mains power interruption.

19. The LHC is a 7 TeV machine and there will necessarily be a significant number of training quenches needed to reach this operating energy. Estimates range from five hundred to over one thousand for this number. The Panel urges a cautious approach to this process until there is more experience with the machine protection system for the magnets but then proceed in a measured fashion. One concern is whether or not the magnets will require retraining under thermal cycling.

20. The governmental mandated annual cleaning of the cooling towers as currently planned will involve an annual thermal cycling of the magnet system due to the shut-down of the cryogenic plant. This annual cycling will lead to significant long term reliability and availability issues and is therefore not acceptable. The Panel agrees that

the proposed redundant cooling water supply for the cryo plants at the main cryoplant sites that can then keep the machine cold is adequate.

21. The Panel endorses the addition of the burst disks on the beam tube vacuum system to provide overpressure protection for this key system.

The rest of the systems that were discussed during both the Chamonix Workshop and during our two day meeting at CERN appear to represent no or limited risk to the successful long term operation of the LHC at its design energy. These include the kicker systems, the control system, the magnet power supply systems and the cryogenic system.

The improvements to the LHC that are required for its safe initial operation with acceptable risk are:
- the installation and successful commissioning of the complete upgraded QPS system.
- the complete analysis of the quench characteristics of the other magnet circuits and installation and commissioning of any needed modifications indicated by that analysis.
- the planned intermediate upgrade of the cryostat pressure relief system for initial operations.

In closing, the Panel believes that with the successful completion of the required upgrades, the LHC can be operated at 5 TeV with acceptable risk for up to one year pending a thorough analysis of the initial lower energy running. Operating at 5 TeV has one half the stored energy in the magnets compared to 7 TeV and is five times higher in energy than the Tevatron. This running will provide an early understanding of the operational characteristics of the LHC and provide a significant initial data sample for the experiments giving a first look at this exciting new energy region.

Introduction

Risk is a combination of severity and probability. An example is the “risk” of death from flying on commercial airlines. While death from a airplane crash is unquestionably the highest severity, the probability of an airplane crash is exceedingly low, on the order of $1x10^{-9}$, therefore most people consider this an acceptable risk. There are, however, some severities which are not acceptable, no matter how improbable. Risk can be reduced in two ways, either by reducing the severity or by reducing the probability. The Panel has developed its recommendations and observations to arrive at a collective assessment of the risk to the LHC for repair, re-commissioning, and operations until the next shutdown, and slightly beyond based on this premise.

The repairs to the LHC themselves pose a risk to its long term reliable operation in addition to the short term risk due the desire to get the LHC back to an operational state as soon as possible. One area that has potentially significant risk is the installation of the new pressure relief valves on the magnet cryostats. Both the machining of the cryostat which can produce hot chips and the subsequent welding of the valve bodies into the cryostat could ignite the multi-layer insulation (MLI) which is very flammable. Both CERN and other laboratories have experienced these fires. While the procedures described during the presentations to the Panel seem ok, extra vigilance is needed because of the severity of the consequences. While making the atmosphere inert in the area of the machining and welding would provide extra safety margin, management of this in the closed environment of the tunnel imposes a heavy burden to insure personnel safety. The Panel feels that the procedures in place are probably sufficient provided an extra person is always present with appropriate fire suppression equipment at hand.

The repair schedule is aggressive, and has a concern for safety and quality, both of which are paramount to the successful repair and subsequent operation of the LHC. The concern is that both safety and quality will suffer as time goes by. Schedule delays, holidays and the summer months, and additional tasks added to an already burgeoning workload will put pressure on safety compliance, quality inspection, and testing. It cannot be refuted that issues with quality and a complex and complicated design are responsible for the incident of September 19, 2008. The quality program presented in March 2009 appears to be decentralized and highly dependent upon the individuals for success. This isn't to say that it cannot work, but the success depends upon the presence of those individuals and could break down if those individuals were not present for a period of time or during critical-path times. Management will need to be vigilant in their oversight of both programs to assure the success of the repairs.

With this overview on risk and safety, the areas of concern will be discussed in some detail below.

Magnet Interconnects

The new procedures with photographs, independent monitoring of the temperature attained during the soldering process, and the additional visual inspections appear to provide the needed quality assurance for the high current splices. The Panel, however, continues to feel that adding mechanical clamps for these key splices would add an extra margin of safety. The reinstallation of the magnets in the damage area of sector 34 presents an opportunity to develop and deploy effective mechanical clamps.

The issue of monitoring the integrity of the existing high current splices remains a concern. It is unfortunate that the tomographic high energy x-ray machine will not be available until late summer after all the relief valve installation has been completed. From the data presented to the Panel, it appears that this technique would have adequate resolution to identify lack of solder filling the void at the end of the splice components to provide the needed longitudinal conductivity of the non-superconducting part of the magnet buses. Measuring the resistance of the bus just above the superconducting transition temperature has been suggested as a way of monitoring this. With a length of at least 14 meters of bus as part of the splice circuit between voltage taps sensing say five millimeters of one half the bus missing would require an absolute resistance measurement of a part in 10^4. While this would be possible with sufficient signal averaging in a distributed system, the systematic effects of the exact location of the voltage taps and the mechanical variation of the bus itself are much larger. This makes the required absolute resistance measurement impossible.

Conventional radiography of the splice area using a gamma source from outside the LHe tube is another possibility. While the resolution will be poorer than if the x-ray film were placed directly behind the splice area, it may be sufficient to identify gaps of more than one or two millimeters. The remaining thirteen to fourteen millimeters of overlap of the copper saddle and wedge should be sufficient to insure adequate longitudinal quench propagation in these splices into the bus. Tests should be carried out to see if the resolution is sufficient to identify these gaps.

Control System

The redundant UPS system powering the Central Control Center and its server farm next door will provide full control of the LHC for 10 minutes after a complete mains power cut to the CCC. After that parts of the system fail sequentially until the entire system is dead after one hour. The ten minutes live time while short appears to be adequate to put the LHC in a known safe state in the event of such a failure. Prudence would suggest exploring the possibility of providing additional backup power, either through diesel powered generators or switching to an alternate source of mains power to insure that there is no possibility of losing control of the LHC. This control continuity would also make the recovery from such an event much faster.

One feature that came to light during the presentations on the control system was the fact that the room housing the server farm for the control system has liquid water cooling piping running in the ceiling above the servers. A failure of this piping would allow water to fall on the servers effectively destroying a significant fraction of the servers. Depending on the extent of the damage, the LHC could be off for up to six months while the damaged servers were replaced and the server farm re-commissioned. The Panel recommends that suitable shields be installed to prevent water from hitting the servers in the event of a failure in this piping.

The data archives for all the system monitoring by the control system are in a separate location and provide excellent redundancy.

Cooling Towers

French law now requires careful monitoring of the bacterial activity of cooling towers and an annual shutdown for cleaning. While the cooling towers at each of the cryoplant locations are segmented and individual sections can be operated independently, the sections share a common sump. This means that the entire tower must be shutdown to carry out the required cleaning. This means that the cryoplant(s) serving the adjacent two sectors must be shut down. The cleaning of the towers is only a two to three day task but the recovery of the cryoplants is a two to three week affair. The temperature rise of the magnets during this period will be in the neighborhood of 80 ^{o}K with significant thermal expansion of the cold masses. There is a risk that the PIMs will bind resulting in one of the fingers protruding into the beam tube. This would require warming up to room temperature and then cooling back down requiring two months. This is an unacceptable operational hazard even taking into account the annual winter shutdown during which it is planned to keep the LHC cold.

There are plans to install a smaller redundant cooling tower with sufficient capacity to operate one of the cryoplants during the shutdown of the main cooling tower. One of the good outcomes of the September 19 incident has been the series of cryo system tests using heaters that have shown that one cryo plant has sufficient capacity to cool both adjacent sectors during normal operation. The extra capacity provided by the second plant is essential for cool down and the electricity savings by operating only one plant during normal operations amounts to more than 5 MCHF per year.

The Panel supports the construction of the four additional cooling towers to provide the needed redundancy for the required annual cleaning of the towers.

Kicker Magnets

The LHC has two kicker magnet systems for each beam. The injection kickers kick the injected beam onto the central orbit in the ring and the extraction kickers remove the beam from the ring out through an extraction channel which contains dilution kickers to limit the power density on the graphite beam dump. The injection kickers only have enough bend to bend the 450 GeV beam from the SPS on the stable orbit. They are powered only during the injection process and hence do not represent a risk during ramping and colliding beam operation at energy. Misfiring can cause quenches but pose no risk for permanent damage to collider components. The extraction kicker is a set of 15 kicker modules with sufficient strength that only 14 of the modules can cleanly extract the beam from the machine. The modules are fired during the beam abort gap to avoid kicking beam particles while the magnetic field in the kicker modules is ramping up to full field. The power supply for these kickers must track the beam energy accurately and does so by comparing the dipole current in three adjacent sectors and uses the result to set the power supply voltage. If one of the modules fires by accident the trigger logic detects this and fires the rest of the modules to extract the beam. Because this is asynchronous with the abort gap in the beam, two or three bunches will not see the full field and will miss the extraction channel probably striking down stream magnets and causing them to quench . The total power in these few bunches is not sufficient to damage any of the collider components.

The fail safe designs of the systems with redundancy in the case of the extraction kickers and the limited power and on time of the injection kickers imply low risk. In addition, the rigorous test and monitoring program carried out by the group in charge of the kicker magnet system provides a significant further reduction of risk to the LHC. For the long term operability of the LHC, it will be important to maintain this rigorous test and monitoring program. With this in place, the kicker systems do not represent a risk to the safe long term operability of the LHC.

Quench Protection System

A separate external review panel (Quench Protection System Review Panel) was convened to assess the safety of the enhanced quench protection system for the high current main quadrupole system and the high current main dipole magnet system. The separate panel has met with appropriate CERN staff and have issued their primary conclusions from that review (Ref. 3). Their key recommendation was that the LHC main buses not be operated until the full upgraded quench protection system is installed and commissioned. While this is the most conservative position with respect to operating these key systems, it does preclude parallel efforts to identify other possible resistive bus joints and repair/replace them during the current shutdown. We recommend that a careful analysis be carried out to determine a safe low current that the buses could be operated at to enable this parallel effort for detection of these possible flaws. Otherwise we strongly endorse the QPS Panel's conclusions.

RF System

The LHC RF system consists of two cryomodules per ring with each module containing four single cell 400 MHz superconducting RF cavities operating at an accelerating gradient of 5.5 MV/m. This provides a total accelerating voltage of 16 MV per ring. While this is a relatively modest accelerating gradient for modern superconducting RF cavities the reactive power of the beam requires couplers with high power capability. The cavities are the same type as those used for LEP constructed by sputter coating electropolished copper cavities with several microns of Nb to provide the superconducting surface. As with all superconducting RF cavities, cleanliness is paramount for their successful operation.

The RF system is located at IP 4 with one cryomodule for each beam located on each side of the IP. On September 19, the automatic gate valves closed rapidly enough so that the shock pressure wave in the beam tube did not reach the cavities. The RF system is located about 2 km from the center of the damage region of Sector 34. The cavities were at 4.2 degrees at the time and filled with LHe and the gate valves were open. Had the beam tube reached atmospheric pressure at the cavity location, the LHe would have flashed increasing the pressure in the He vessel to 12 bar causing significant mechanical damage to the cavities. This is due to 50 mm diameter piping to the pressure relief valve from the He vessel. The release of approximately 6 tonnes of LHe into sector 34 caused an overpressure of the tunnel by between 0.1 and 0.25 bar which led to the distortion of the ventilation door at IP4. Had this door fallen on the beam tubes the LHC would have been off for more than one year since there is only one spare cryomodule and four cavities that could be installed in one of the damaged cryomodules removed from the tunnel. This would allow low luminosity running of the LHC until two more cryomodules were repaired and reinstalled.

The Panel strongly recommends developing and installing a suitable mechanical protection system for the beam tubes in the vicinity of the cavities to avoid sudden rupture of the beam tube vacuum.

The other concern with respect to the RF system is the danger of migration of the MLI fragment into the cavities. If any of these fragments get into the cavities, the Nb surface will be destroyed and the cavity will have to be replaced. While the MLI fragments are aluminized on one side, the other is a polyester material which will charge up in the presence of the proton beam. This charging up may enable migration of these fragments over significant distances and it is not impossible that they could reach the RF cavities. The Panel urges periodic inspection of the room temperature beam tubes near the RF cavities to look for these migrating fragments. The overhead in re-activating the NEG pumps in this region is well worth the risk reduction for this catastrophic failure mechanism for the RF cavities.

The transverse RF kickers in this region are much more robust and do not represent a significant risk to the startup of the LHC.

Vacuum System

The beam tube vacuum system was ruptured during the incident on September 19 which led to contamination of the beam pipe with soot particles from the arcs and with MLI fragments generated during the rapid flashing of the LHe and the subsequent over-pressuring of the magnet cryostats. The mechanical scrubbing of the inner surface of the beam tube with sponge like material impregnated with alcohol followed by using the same material dry appears to have done a good job in cleaning up the inner surface of the beam tube.

The creative vacuum cleaning along with the puffer system to recover the MLI fragments that are between the outer beam tube wall and the inner bore of the magnets appears to be very successful. The PIM interconnects will certainly have residual MLI fragments in the trapping regions of their mechanical structure. It is these areas that are a potential source of the migrating fragments mentioned in the RF section above.

The Panel recommends that warm sections of the beam tube vacuum system be monitored for these fragments.

The Panel agrees with the proposed installation of a pressure relief system for the beam tube vacuum system to avoid overpressuring this sensitive system should an incident similar to September 19 occur in the future.

Site Power

A separate conversation by the Panel Chair with XXX who heads the site power management group to explore the vulnerability of LHC operations to site power interruptions. One of the principal concerns is the age of the electrical power infrastructure most of which was installed during the construction of LEP. The failure of a large transformer the week before the initial injection of beam into the LHC on September 10 nearly jeopardized that event which received international press attention.

Fortunately a similar transformer that was not being used by CMS was moved to replace the failed transformer and the commissioning could continue.

The other area of concern is lightning strikes to the French Grid that provides the bulk of the electricity to the CERN site. Modern variable frequency drive systems for large electric motors are particularly vulnerable to short (a few cycle) interruptions of power caused by these strikes. CERN engineers have worked hard to identify these sensitivities and developed circuitry to minimize these dropouts. The cryogenics plants were among the most sensitive and the effects on operations the largest. The present cryoplant system is now much more robust.

Machine protection systems like the beam abort system, the quench protection system, and the control system are all on UPS backup systems with a operation time sufficient to carry out the protection function. These UPS systems are monitored and any failure triggers the machine safety interlock system dropping the beam permit.

Beam Dumps

The full stored energy of the LHC beam must be absorbed by the beam dumps when the beam is aborted. The dumps are made from graphite that has very high thermal conductivity to spread the deposited energy as rapidly as possible. If the beam were to hit only one spot, it would immediately vaporize the graphite and to avoid this there is a set of kickers in the extraction channel that paint the beam over a larger area.

Magnet Cryostat Pressure Relief System

The inadequacy of the magnet cryostat pressure relief system to cope with the large loss rate of liquid He led to much more extensive damage to the LHC magnet system during the September 19 incident. The pressure in the cryostat reached approximately 7 bar as estimated from the distortion of the outer bellows connecting the adjacent magnet cryostats. This pressure acting against the isolation bellows at each subsector caused extensive displacement of internal and external magnet components. The present pressure relief system was designed to cope with a maximum loss of 2 kg/sec of liquid He where the maximum loss rate during the September 19 incident was 20 kg/sec.

After the September 19 incident and the subsequent analysis of the damaged region, the maximum credible incident (MCI) with respect to the loss rate of liquid He was increased to 40 kg/sec. This takes into account the fact that only two of the four liquid He lines were ruptured by the arc in the September 19 incident.

To limit the maximum pressure excursion for a MCI to the design pressure of 1.5 bar, the total cross sectional area of the pressure relief valves must be increased. The original system has two DN90 valves per sub-sector. The new system will have 15 DN100 “valves” per sub-sector in the sectors that are cold which will be accomplished by replacing the clamping bolts on all the instrumentation ports in each sub-sector with spring loaded restraints. This would limit the maximum pressure excursion to less than the design pressure of 1.5 bar for an incident similar to September 19 but would reach 3 to 4 bar for a MCI event. For the sectors that are warm, a DN200 valve is being installed on each dipole cryostat for a total of 12 valves along and 8 of the DN100 valves are being reconfigured in each sub-sector. With this new configuration for the cryostat pressure relief system, the maximum pressure excursion would be limited to less than the design pressure of 1.5 bar for the MCI.

It is currently thought not possible to install the DN200 valves on the two Q6's and the eight DFBA's in the cold sectors of the LHC before starting up the LHC this year. This risk needs to be carefully analyzed to see if there are possible work-arounds or operational strategies to reduce it to the lowest possible level. Suitable pressure relief valves will be installed in these systems in the sectors that are warm.

If for some reason there is additional schedule delay, CERN management should seriously consider outfitting the rest of the LHC with the full compliment of DN200 valves before starting up the LHC.

At 5 TeV the stored energy in the magnet system is one half that of operating at 7 TeV and thereby represents one half the damage potential. While there is some risk involved in operating the LHC with respect to an MCI with only part of the upgraded pressure relief system installed and its operation validated, the Panel feels that the risk is sufficiently small for operating at energies up to 5 TeV that the startup schedule should not be delayed. The partial system that will be installed before the startup of the LHC will handle an event like the September 19 incident. It is critically important to begin operating the LHC as soon as possible to gain operational experience with this complex machine. This will be the fastest and safest route to the rich physics that we all believe is waiting for us.

Summary

As stated above, the systems that are required for the safe operation of the LHC with acceptable risk are:
- the installation and successful commissioning of the complete upgraded QPS system.
- the complete analysis of the other magnet systems, the inner triplets, the special purpose magnets, etc and the installation and commissioning of any needed modifications indicated by that analysis.
- the planned intermediate upgrade of the cryostat pressure relief system for initial operations.

In closing, the Panel believes that with the successful completion of the required upgrades, the LHC can be operated at 5 TeV with acceptable risk for up to one year pending a thorough analysis of the initial lower energy running. This running will provide an early understanding of the operational characteristics of the LHC and provide a significant initial data sample for the experiments.

References

1. https://espace.cern.ch/acc-tec-sector/Chamonix/Chamx2009/html/session.htm
2. http://cdsweb.cern.ch/record/1168025/files/LHC-PROJECT-REPORT-1168.pdf
3. Draft Report of Quench Protection System Panel in preparation.

Appendix 1

Mandate for External Panel on Risk

Primary source of incident provoked in sector 34?

(Are there any doubts as to the conclusion that this was caused by a high resistance, 200nΩ, splice)

Risk analysis of a similar incident occurring in the future given the proposed mitigation measures.

(Are the mitigation measures sufficient and appropriate?)

(Is the resistance of the busbar and coil splices the correct parameter? What value of resistance is dangerous, influence of the beam energy, i.e. the dipole current. Simulations of the thermal runaway as a function of resistance and dipole current)

(Can there be complete protection in case of a splice rupture, is there enough time to protect?)

(risk associated with re-training to 7TeV)

(effect of beam current)

(effect of high energy beam operation, 5TeV, 6TeV, 7TeV)

Are the measures foreseen for mitigation of collateral damage appropriate?

(damage to magnet interconnects, cold supports, fixations of jacks, and pollution of the vacuum chamber. Is the proposed combination of these mitigating repairs coherent?)

Relative Risks associated with the two most probable start-up scenarios in 2009-2010. i.e. installation of half of the pressure valves followed by beam operation then the other half. Or installation of all valves followed by beam operation.

(risk during "transition" period)

(schedule risks)

(radiation, ALARA risks)

"Comments on Operability of LHC"

(Helium storage, Safety constraints, PIMs constraints, cooling tower maintenance, Electrical Network maintenance, humidity in sector 34 and corrosion….)

Appendix 2

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